A Detailed Comparison of Three Building Energy Modeling Programs: EnergyPlus, DeST, and DOE-2.1E

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Abstract:
Building energy simulation is widely used to help design energy-efficient building envelopes and HVAC systems, to develop and demonstrate compliance of building energy codes, and implement building energy rating programs. However, large discrepancies exist between simulation results from different Building Energy Modeling Programs (BEMPs). This leads to many users and stakeholders lacking confidence in the results from BEMPs and building simulation methods. This paper compared the building thermal load modeling capabilities and simulation results of three BEMPs: EnergyPlus, DeST and DOE-2.1E. Test cases, based upon the ASHRAE Standard 140 tests, were designed to isolate and evaluate the key influencing factors responsible for the discrepancies in results between EnergyPlus and DeST. This included the loads algorithms and some of the default input parameters. It was concluded that there is little difference between the results from EnergyPlus and DeST if the input values are the same or equivalent. This is despite there being many discrepancies between the heat balance algorithms. DOE-2.1E can produce large errors for cases when adjacent zones have very different conditions, or if a zone is conditioned part-time while adjacent zones are unconditioned. This was due to the lack of a strict zonal heat balance routine in DOE-2.1E, and the steady state handling of heat flow through interior walls and partitions. This comparison study did not produce another test suite, but rather a methodology to design tests that can be used to identify and isolate key influencing factors that drive the building thermal loads, and a process with which to carry them out.

Keywords:
Building energy modeling program, building simulation, comparison, DeST, DOE-2.1E, EnergyPlus

1 Introduction

Computer simulation is an important and proven method to help understand and analyze the thermal performance of buildings, and predict their operational energy consumption. Since the 1960s, many Building Energy Modeling Programs (BEMPs) have been developed to perform building energy simulations, including the widely-used DOE-2 (DOE-2 1980), EnergyPlus (Crawley et al. 2001), ESP (ESRU 1999), and DeST (Yan et al. 2008; Zhang et al. 2008). DOE-2 was developed at the Lawrence Berkeley National Laboratory with funding from the U.S. Department of Energy (USDOE) after the energy crisis in late 1970s and is still the most widely-used BEMP in the U.S. This includes its use as a stand-alone calculation engine and with graphical user interfaces (GUI) such as VisualDOE (VisualDOE 2004), EnergyPro (EnergyPro 2011), eQuest (eQuest 2009), and EnergyGauge (EnergyGauge 2012). EnergyPlus is a next generation BEMP developed, supported and maintained by a team led and funded by USDOE since 1996. EnergyPlus is based on the loads algorithms of BLAST and the systems algorithms of DOE-2. New features and enhancements were added to support innovative, low-energy building designs and operational controls. Development of ESP-r started in 1974 at the University of Strathclyde and is primarily used in Europe. DeST (Designer's Simulation Toolkits) is a BEMP developed at Tsinghua University since the late 1980s with the aim of aiding teaching, research and the practical use of building energy analysis and simulations in China.

BEMPs play a significant role in the design of energy efficient envelopes and HVAC systems for new buildings, retrofitting existing buildings, the development of building energy codes and standards, and defining and implementing building energy rating/labeling programs. However, the issue that large discrepancies exist in simulation results between different BEMPs, even for the same building modeled by the same person, leads to many users and stakeholders to lack confidence in building simulation methods and the results from BEMPs. This is a major barrier for the wider adoption and effective application of building energy simulation, and represents a challenge to the industry. The large discrepancies of simulation results between different BEMPs mainly come from three factors: first is the simulation engine that is the unchangeable core; second is the GUI to the simulation engine that usually simplifies, hides or hard-wires some inputs that can be important; third is the fact that users may model the building or system inaccurately as they are not familiar with the chosen BEMP, or input poor data due to constraints of budget and resources. In order to address these issues, the impact of the above three factors must be identified and quantified.

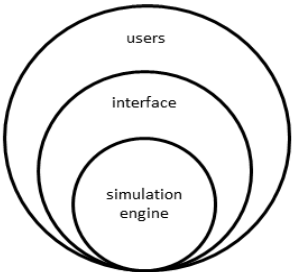

Figure 1 The top three influencing factors for the discrepancies in simulation results between the different BEMPs

This paper mainly discusses why and how different BEMPs produce different simulation results. As the building load calculation forms the basis of building energy and environmental performance simulations, this paper focuses on detailed comparisons of load calculations between the three BEMPs: EnergyPlus, DeST, and DOE-2.1E, with the goal to identify and quantify the influences of the simulation engines and input values or algorithms. EnergyPlus was chosen because it is widely used and continuously being developed and supported by USDOE. DOE-2.1E was chosen as it is still widely used in the U.S. DeST was chosen due to its emerging use in China and a few Asian countries and regions. Top-level key features of DOE-2.1E, DeST and EnergyPlus are summarized in Table 1.

Our findings can be a valuable reference for decision makers to determine which BEMP to use for various applications including development and compliance calculations for building energy codes and standards. Another separate paper will discuss methodologies and findings from a detailed comparison of the same three BEMPs in HVAC systems and central plant modeling.

Table 1 Comparison of Top-level Key Features of DOE-2.1E, DeST and EnergyPlus

Feature	DOE-2.1E	DeST	EnergyPlus
Developer	LBNL/USDOE	Tsinghua University, China	USDOE
Development and Support	No more development or support	On-going	On-going
Users	Worldwide	Mostly China	Worldwide
Inputs	Text, BDL	Database, Microsoft Access	Text, IDF
Outputs	Summary & hourly reports	Summary & hourly reports	Extensive summary & detailed reports with user specified time steps
GUI	Simulation engine only; 3rd party GUIs available	Coupled with AutoCAD	Simulation engine only; 3rd party GUIs available
Algorithms	Surface heat transfer: CTF; Zone weighting factors	Zone heat balance: State Space Method	Surface heat balance: CTF; Zone heat balance
Time Step	1 hour, fixed	1 hour, fixed	1 to 60 minutes (15 minutes is used in the tests)
Weather Data	Hourly	Hourly	Hourly or sub-hourly
HVAC	28 pre-defined systems	A few pre-defined systems	User configurable with some limitations
User Customization	User functions	N/A	Energy Management Systems
Co-Simulation	N/A	N/A	External Interface
Language	Fortran 77	C++	Fortran 2003
Limitations	Lack zone air heat balance, linear systems	Limited user customization, linear systems	Potentially long run-time for large models
Licensing	Free download; Source code available	Free download; Source code not open to public	Free download; Open source

2 Methodology

The comparison of the features and capabilities of twenty major BEMPs were summarized to help understand their functions, advantages and disadvantages from a simple overview (Crawley et al. 2008). Many efforts to test and validate simulation results from EnergyPlus (Henninger et al.2011a; Henninger et al.2011b; Henninger et al.2011c), DeST (DeST 2006), and DOE-2.1E (IEA 1995; Sullivan et al. 1998; Henninger et al. 2006; Meldem et al. 1995) have been undertaken by their development teams. The validation work employed three testing approaches: analytical tests, comparative (inter-program) tests, and empirical tests. LBNL performed comparative tests between DOE-2.1E and EnergyPlus based on the test cases defined in the Alternate Calculation Method Manual of California Building Energy Efficiency Standards Title 24, (REF) to evaluate the possibility of using EnergyPlus as the reference simulation engine for development and compliance calculations of future revisions of Title 24 (Huang et al. 2006). A key finding was that the simulation results were highly sensitive to seemingly minor differences in inputs and model algorithms. Another comparison (Andolsun et al. 2010) of EnergyPlus and DOE-2.1E was undertaken using case studies that ranged from a sealed box to a detailed residential building. Andolsun et al. demonstrated that EnergyPlus under-estimated total building loads by 16-17% compared to DOE-2.1E as incremental loads were added, and air infiltration reduced the differences of loads calculation results between the two BEMPs. Another study (Waddell et al. 2010) compared the results of solar gains, cooling load calculations, and the transition from the solar gains to cooling loads, from a few BEMPs including EnergyPlus, eQuest, IES, and TRACE 700. This validation and comparison work demonstrated that the three BEMPs had the basic capability to simulate dynamic thermal processes and the energy performance of buildings, but also uncovered that large discrepancies existed in the results from DOE-2.1E and EnergyPlus which were not well understood, nor did they explain what the key influencing factors could be.

Previous building simulation comparison work has generally resulted in standard test suites or case studies, which present the discrepancies between the simulation results, but do not address specific reasons for the discrepancies from the view of calculation algorithms or model inputs. In this paper, new sets of in-depth tests were designed and carried out as complement to the ASHRAE Standard 140 tests. To further identify and understand the differences and their effects on simulation results between EnergyPlus and DeST, new test cases were designed by modifying inputs of the ASHRAE Standard 140 tests, based on deep understandings of load calculation algorithms, modeling assumptions, and defaults of inputs of the three BEMPs. It should be noted that all test cases in ASHRAE Standard 140 were set to be continuously (24 hours per day) conditioned by mechanical cooling and heating systems. However, it is very common that heating or cooling is only used during some specific hours, or only in specific rooms of a building. This means heat transfer between unconditioned and conditioned spaces need to be accurately accounted for in the heat balance calculations. Therefore, test cases with two adjacent spaces were created, and special thermal conditions and practical engineering conditions were applied to test possible limitations of the three BEMPs. For all test cases, EnergyPlus Version 7.0, DeST Version 2011-11-23 and DOE-2.1E114 were used. For all EnergyPlus tests, the CTF (Conduction Transfer Function) method was used with a simulation time-step of 15 minutes. Figure 2 summarizes the method used to develop the tests and perform the comparisons.

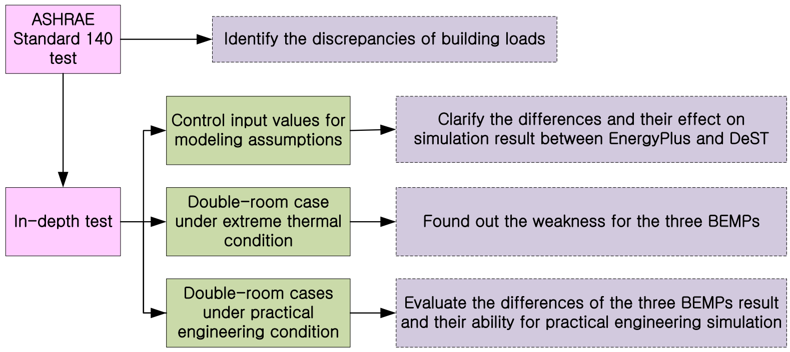

Figure 2 Methodology to Build the Tests and Perform Comparisons

3 Results from the ASHRAE Standard 140 Tests

ASHRAE Standard 140-2007, Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs, is based on work previously performed by the International Energy Agency (IEA) under the Building Energy Simulation Test (BESTEST) and Diagnostic Method (IEA 1995). ASHRAE Standard 140 defines a standard method of tests that can be used for identifying and diagnosing predictive differences from whole building BEMPs that may possibly be caused by algorithmic differences, modeling limitations, input differences, or coding errors. So, the load calculation comparison based on ASHRAE Standard 140 tests is carried out first in our study. The results for DOE-2.1E were obtained from ASHRAE Standard 140; results for EnergyPlus 7.0 were obtained from the EnergyPlus development team; while results for DeST were produced during this study as earlier tests were limited and outdated.

All test cases used single-room models except Case 960. Parameters including weather data, building construction, envelope materials, infiltration, internal loads, and mechanical system are controlled in each of the three BEMPs. Case 600 is the base test, Case 610 to 650 are low-mass tests, Case 900 to 960 are high-mass tests, Case 600FF to 950FF are free flow tests and the remaining are additional test cases (Case 195 to 320, Case 395 to 440 and Case 800 to 810). The outputs from these test cases were annual heating and cooling loads, peak heating and cooling loads, and room temperatures for the cases without mechanical heating or cooling systems. The annual heating loads for the low mass building are showed in Figure 3, where each bar represents a different BEMP, from DOE-2, BLAST (BLAST 1991), ESP, SRES/SUN, SERIRES, S3PAS, TRNSYS (http://sel.me.wisc.edu/trnsys), TASE (Aittomäki et al. 1976), ENERGYPLUS, or DEST.

Table 2 BEMPs participating in the ASHRAE 140 comparison (Henninger et al.2011b)

Code Name	**Computer program**	**Developer**	**Implemented by**
BLAST	BLAST-3.0 level 193 v.1	CERL,U.S.	NREL, U.S. Politecnico, Torino, Italy
DOE2.1D	DOE2.1D 14	LANL/LBL,U.S.	NREL, U.S.
ESP	ESP-RV8	Strathclyde University, U.K.	De Montfort University, U.K.
SRES/SUN	SERIRES/SUNCODE 5.7	NREL/Ecotope, U.S.	NREL, U.S.
SERIRES	SERIRES 1.2	NREL, U.S. and BRE, U.K.	BRE, U.K.
S3PAS	S3PAS	University of Sevilla, Spain	University of Sevilla, Spain
TASE	TASE	Tampere University, Finland	Tampere University, Finland
TRNSYS	TRNSYS 13.1	University of Wisconsin, U.S.	BRE, U.K. Vrije Universiteit, Brussels, Belgium
DOE2.1E	DOE2.1E	LANL/LBL, U.S.	GARD Analytics, U.S. using NREL input files
DOE2.1E-RevWindow	DOE2.1E-RevWindow	LANL/LBL, U.S.	GARD Analytics, U.S. Uses Window 4 data file which more closely matches specification
BLAST3.0-334	BLAST3.0 level 334	CERL, U.S.	GARD Analytics, U.S. using NREL input files
ENERGY PLUS	EnergyPlus ver.7.0.0.036,Nov 2011	U.S Dept. of Energy	GARD Analytics, U.S.
DEST	DeST 2011-11-23	Tsinghua University, China	Tsinghua University, China

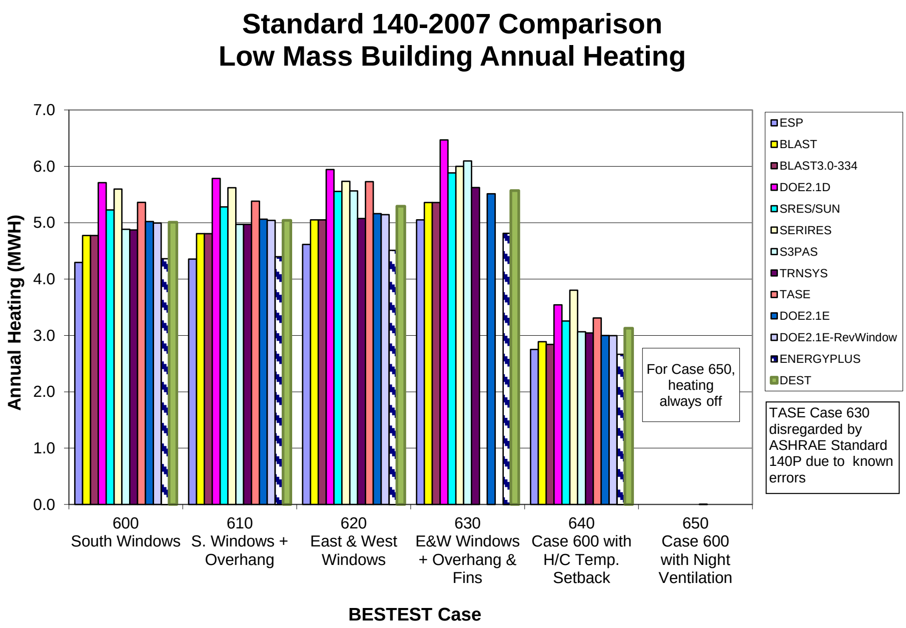

Figure 3 Annual Heating Loads for the 600 Series Low-Mass Tests from the ASHRAE Standard 140-2007

One method to see how well DOE-2.1E (the output of DOE2.1E-RevWindow), DeST, and EnergyPlus predict building loads is to see if their results fall within the range of spread of results from other BEMPs. Tables 3 to 7 show the same results as Figure 3 but with an extra column for each of the three BEMPs to indicate whether its results fall within the ranges. The tables show the minimum and maximum results from all of the tested BEMPs except DOE-2.1E, DeST and EnergyPlus. An indicator of 'y' in black means that the test result are within the [Min., Max.] range, a 'y' in yellow means the results are not within the [Min., Max.] range but are within the 5% relaxed range [Min./1.05, Max.*1.05], while an 'n' in red means the results were outside of the relaxed range [Min./1.05, Max.*1.05].

Table 3 Comparison of Annual Heating Loads

ANNUAL HEATING LOADS (MWh)										
Case	**Description**	**Min.**	**Max.**	**DOE-2.1E**		**DeST**		**EnergyPlus**		
600	Base Case	4.296	5.709	4.994	y	5.007	y	4.364	y	
610	South Shading	4.355	5.786	5.042	y	5.042	y	4.398	y	
620	East/West Window Orientation	4.613	5.944	5.144	y	5.292	y	4.512	**y**	
630	East/West Shading	5.050	6.469	5.508	y	5.570	y	4.813	**y**	
640	Thermostat Setback	2.751	3.803	2.995	y	3.127	y	2.667	**y**	
650	Night Ventilation	0.000	0.000	0.000	y	0.000	y	0.000	y	
900	High-Mass Base Case	1.170	2.041	1.301	y	1.894	y	1.163	**y**	
910	High-Mass South Shading	1.512	2.282	1.559	y	2.266	y	1.427	**n**	
920	High-Mass East/West Window Orientation	3.261	4.300	3.312	y	4.025	y	3.087	**n**	
930	High-Mass East/West Shading	4.143	5.335	4.249	y	4.485	y	3.785	**n**	
940	High-Mass Thermostat Setback	0.793	1.411	0.838	y	1.270	y	0.727	**n**	
950	High-Mass Night Ventilation	0.000	0.000	0.000	y	0.000	y	0.000	y	
960	Sunspace	2.144	3.373	2.216	y	2.835	y	2.322	y	

Table 4 Comparison of Annual Cooling Loads

ANNUAL COOLING LOADS (MWh)									
Case	**Description**	**Min.**	**Max.**	**DOE-2.1E**		**DeST**		**EnergyPlus**	
600	Base Case	6.137	8.448	8.054	y	5.924	y	7.006	y
610	South Shading	3.915	6.139	5.874	y	4.873	y	4.976	y
620	East/West Window Orientation	3.417	5.482	5.256	y	3.847	y	4.384	y
630	East/West Shading	2.129	3.701	3.235	y	2.879	y	2.952	y
640	Thermostat Setback	5.952	8.097	7.713	y	5.759	y	6.710	y
650	Night Ventilation	4.816	7.064	6.678	y	4.625	y	5.538	y
900	High-Mass Base Case	2.132	3.669	3.390	y	2.296	y	2.683	y
910	High-Mass South Shading	0.821	1.883	1.738	y	1.202	y	1.350	y
920	High-Mass East/West Window Orientation	1.840	3.313	3.169	y	2.401	y	2.683	y
930	High-Mass East/West Shading	1.039	2.238	1.823	y	1.696	y	1.745	y
940	High-Mass Thermostat Setback	2.079	3.546	3.272	y	2.262	y	2.606	y
950	High-Mass Night Ventilation	0.387	0.921	0.749	y	0.455	y	0.571	y
960	Sunspace	0.411	0.895	0.855	y	0.537	y	0.732	y

Table 5 Comparison of Peak Heating Loads

PEAK HEATING LOADS (kW)										
Case	**Description**	**Min.**	**Max.**	**DOE-2.1E**		**DeST**		**EnergyPlus**	
600	Base Case	3.437	4.354	3.767	y	3.986	y	3.732	y
610	South Shading	3.437	4.354	3.755	y	3.954	y	3.720	y
620	East/West Window Orientation	3.591	4.379	3.785	y	3.962	y	3.726	y
630	East/West Shading	3.592	4.280	3.762	y	3.963	y	3.703	y
640	Thermostat Setback	5.232	6.954	5.656	y	5.991	y	6.265	y
650	Night Ventilation	0.000	0.000	0.000	y	0.000	y	0.000	y
900	High-Mass Base Case	2.850	3.797	3.248	y	3.600	y	3.140	y
910	High-Mass South Shading	2.858	3.801	3.256	y	3.612	y	3.139	y
920	High-Mass East/West Window Orientation	3.308	4.061	3.508	y	3.776	y	3.453	y
930	High-Mass East/West Shading	3.355	4.064	3.536	y	3.801	y	3.475	y
940	High-Mass Thermostat Setback	3.980	6.428	5.322	y	5.723	y	4.785	y
950	High-Mass Night Ventilation	0.000	0.000	0.000	y	0.000	y	0.000	y
960	Sunspace	2.410	2.863	2.603	y	2.601	y	2.691	y

Table 6 Comparison of Peak Cooling Loads

PEAK COOLING LOADS (kW)										
Case	**Description**	**Min.**	**Max.**	**DOE-2.1E**		**DeST**		**EnergyPlus**		
600	Base Case	5.965	7.188	6.965	y	6.151	y	6.678	y	
610	South Shading	5.669	6.673	6.482	y	5.964	y	6.274	y	
620	East/West Window Orientation	3.634	5.096	4.679	y	3.819	y	4.005	y	
630	East/West Shading	3.072	4.116	3.834	y	3.270	y	3.446	y	
640	Thermostat Setback	5.884	7.126	6.903	y	6.116	y	6.614	y	
650	Night Ventilation	5.831	7.068	6.843	y	5.973	y	6.479	y	
900	High-Mass Base Case	2.888	3.932	3.778	y	3.469	y	3.320	y	
910	High-Mass South Shading	1.896	3.277	2.703	y	2.953	y	2.640	y	
920	High-Mass East/West Window Orientation	2.385	3.505	3.342	y	2.844	y	2.835	y	
930	High-Mass East/West Shading	1.873	3.080	2.638	y	2.527	y	2.332	y	
940	High-Mass Thermostat Setback	2.888	3.932	3.778	y	3.497	y	3.320	y	
950	High-Mass Night Ventilation	2.033	3.170	2.917	y	2.586	y	2.451	y	
960	Sunspace	0.953	1.422	1.048	y	1.085	y	1.213	y	

Table 7 Comparison of Hourly Zone Temperatures

MAXIMUM ANNUAL HOURLY ZONE TEMPERATURE (℃)										
		Min.	**Max.**	**DOE-2.1E**		**DeST**		**EnergyPlus**	
600FF	Base Case	64.90	75.10	73.40	y	65.49	y	66.03	y
650FF	Night Ventilation	41.81	46.40	45.50	y	42.39	y	43.65	y
900FF	High-Mass Base Case	63.24	73.50	71.70	y	63.67	y	64.31	y
950FF	High-Mass Base Case	35.54	38.50	37.10	y	35.67	y	36.90	y
960FF	Sunspace	48.88	55.34	51.60	y	55.54	y	52.93	y
MINIMUM ANNUAL HOURLY ZONE TEMPERATURE (℃)									
		Min.	**Max.**	**DOE-2.1E**		**DeST**		**EnergyPlus**	
600FF	Base Case	-18.80	-15.57	-17.70	y	-18.60	y	-17.51	y
650FF	Night Ventilation	-6.38	-1.65	-2.00	y	-4.50	y	-2.39	y
900FF	High-Mass Base Case	-23.00	-21.10	-21.00	y	-22.91	y	-23.08	y
950FF	High-Mass Base Case	-20.20	-17.80	-17.80	y	-19.97	y	-20.34	y
960FF	Sunspace	-2.82	5.80	6.00	y	0.48	y	2.44	y
AVERAGE ANNUAL HOURLY ZONE TEMPERATURE (℃)									
		Min.	**Max.**	**DOE-2.1E**		**DeST**		**EnergyPlus**	
600FF	Base Case	24.22	27.40			24.43	y	26.19	y
650FF	Night Ventilation	24.45	27.50			24.45	y	26.40	y
900FF	High-Mass Base Case	17.99	20.80			17.81	y	18.87	y
950FF	High-Mass Base Case	14.00	15.30			13.88	y	14.62	y
960FF	Sunspace	26.43	30.50			29.92	y	29.51	y

From the comparison of the ASHRAE Standard 140 test results, we can see that the simulation results from the three BEMPs mostly fall within the ranges except the heating loads results for the high-mass cases 910, 920, 930, and 940, where EnergyPlus calculated smaller annual heating loads than DOE-2.1E and DeST. EnergyPlus results for these four cases are about 10% lower than the minimum of the ranges. The largest percent differences are in the annual heating loads from test case 940 High-Mass with Thermostat Setback, where EnergyPlus gave the lowest annual heating loads of 0.727 MWh while DeST gave the highest result of 1.27 MWh, a 42.7% difference, even though the absolute difference is not the largest (0.938 MWh in Case 920). The largest percent differences are in the annual cooling loads from test case 950 High-Mass Night Ventilation, where DOE-2.1 gave the highest annual cooling loads of 0.945 MWh while DeST gave the lowest result of 0.455 MWh, a 39.3% difference, even though the absolute difference is not the largest (2.130 MWh in Case 600). For peak heating and cooling loads in Tables 3 and 4, the results from the three BEMPs fall within the ranges, but there are still large difference of 16.4% in case 940 peak heating loads and 18.4% in case 620 peak cooling loads.

Even though test cases from ASHRAE Standard 140 are very simple, there are still large discrepancies in the results from the three BEMPs - especially the annual heating loads for the high-mass test cases. The ASHRAE Standard 140 tests did not provide adequate details to explain or isolate the influencing factors that drive the discrepancies.

4 In-Depth Tests

In order to further compare EnergyPlus, DeST and DOE-2.1E, a suite of in-depth tests were designed and implemented to identify and quantify the key influencing factors that drive the discrepancies between results from the ASHRAE 140 tests.

4.1 Control Input Values Based on ASHRAE Standard 140 Tests

4.1.2 Specification of test cases

A series of tests were designed to identify the influence of different modeling assumptions between DeST and EnergyPlus, as shown in Table 8. When using default values or algorithms in EnergyPlus and DeST, there are large differences in the surface convection coefficients, as shown in Figure 4. DeST assumes constant values for the inside and outside surfaces convection coefficients (DeST 2006), while EnergyPlus calculates these coefficients using indoor and outdoor air temperatures and wind speeds (EnergyPlus 2010). In all test cases except C10, the exterior and interior surfaces convection coefficients for EnergyPlus were set to be the same constant values as those used in DeST.

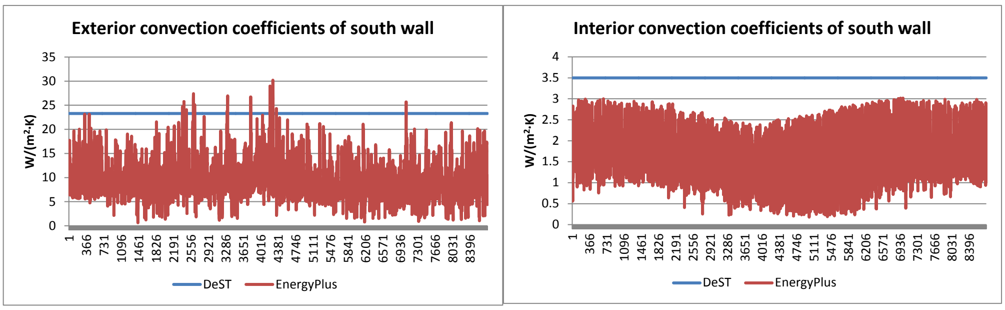

Figure 4 Hourly surface convection coefficients from Case 195 in ASHRAE Standard 140 tests

C1 is the simplest case and can be calculated analytically. It assumes no solar absorption, no long-wave radiant exchange between interior surfaces, and constant outdoor air temperature. C3 is the same as case 195 except the surface convection coefficients are set to the constant value used in DeST. Based on C3, other influencing factors such as internal gains, air infiltration, thermostat control strategy, and a south-facing window were added step by step to build the final C10 test case.

Table 8 In-depth Test Cases

Case	Description
C1	Case 195 + suspended in outdoor air + all absorptances equal zero + outdoor air temperature kept at 10℃
C2	Case 195 + suspended in outdoor air + all absorptances equal zero + ASHRAE Standard 140 weather data
C3	Case 195+ surfaces convection coefficients for EnergyPlus were set to be the same constant values as those used in DeST
C4	C3 + solar absorptance equals 0.6
C5	C4 + infrared emissivity equals 0.9
C6	C5 + internal gains
C7	C6 + air infiltration
C8	C7 + the thermostat control strategy of Case 600
C9	C8 + south windows of Case 600
C10	C9 + time-varied surface convection coefficients for EnergyPlus (exactly the same as Case 600 in the ASHRAE Standard 140-2007)

4.1.2 Results and Discussions

Annual heating and cooling loads for the ten test cases are summarized in Figure 5 and Figure 6.

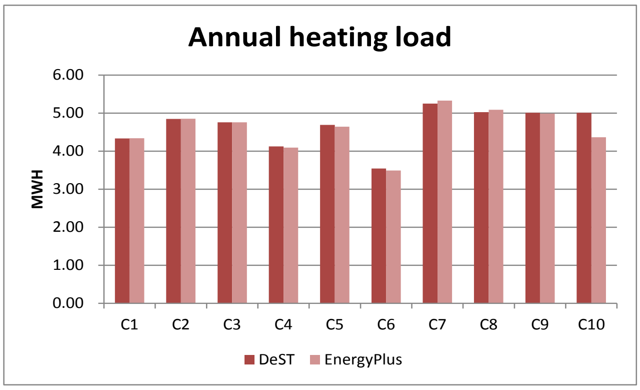

Figure 5 Annual Heating Loads of Test Cases C1 to C10 from EnergyPlus and DeST

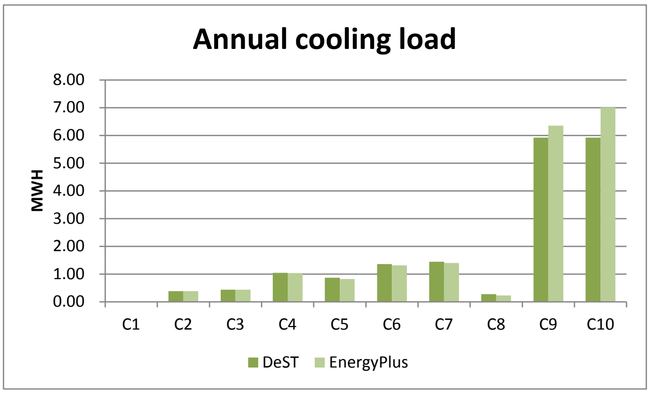

Figure 6 Annual Cooling Loads of Test Cases C1 to C10 from EnergyPlus and DeST

The hourly heating load of test case C1 can be calculated analytically to obtain the result of 0.495 kW, as Table 9 illustrates. The simulation results from DeST and EnergyPlus match the analytical result, as shown in Figure 7.

Table 9 the UA Calculation of Case C1

	h_out **W/(m²·K)**	**R** **(m²·K) /W**	**h_in** **W/(m²·K)**	**Area** **m²**	**U-factor** **W/(m²·K)**	**UA** **W/ K**
Light wall	23.3	1.789	3.5	75.6	0.47	35.70
Light floor	0	25.254	4	48	0.04	1.88
Light roof	23.3	2.993	1	48	0.25	11.89
Total						49.48

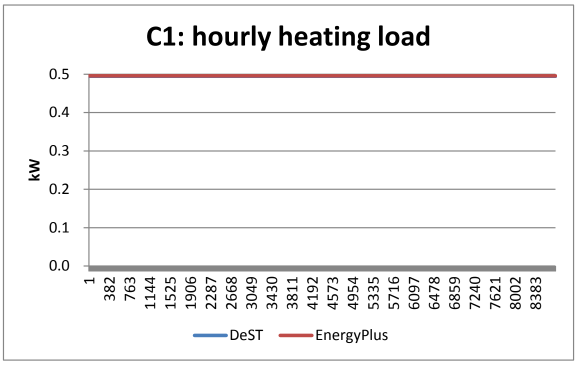

Figure 7 Hourly Heating Load for Case C1

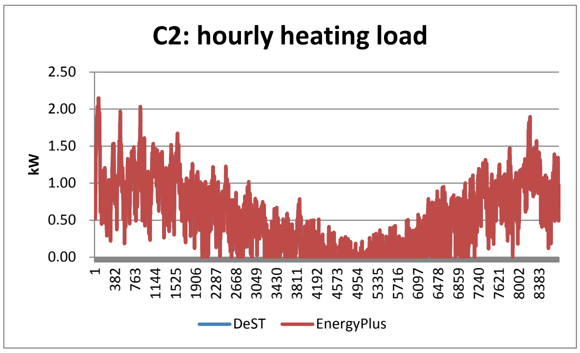

Figure 8 Hourly Heating Load for Case C2

Case C2 considers the hourly variation of outdoor air temperature and the simulation results indicate little differences between DeST and EnergyPlus, as shown in Figure 8.

Comparing the simulation results from EnergyPlus and DeST for cases C1 to C9, we find that the largest discrepancy occurred after south-facing windows were added. The solar transmittance at different incident angles for the double-pane window are almost the same in DeST and EnergyPlus, which are also close to the values provided in ASHRAE Standard 140, as shown in Figure 9. This indicates that the window algorithm should cause little difference between the results from DeST and EnergyPlus. However, when comparing the solar radiation on the southern exterior surface and window-transmitted solar as shown in Figure 10, we found that the annual solar radiation on the south wall from DeST is about 5.1% smaller than from EnergyPlus, while the window-transmitted solar radiation is 7.0% smaller. This helps explain why cooling loads from DeST are lower than EnergyPlus as less solar radiation enters the room.

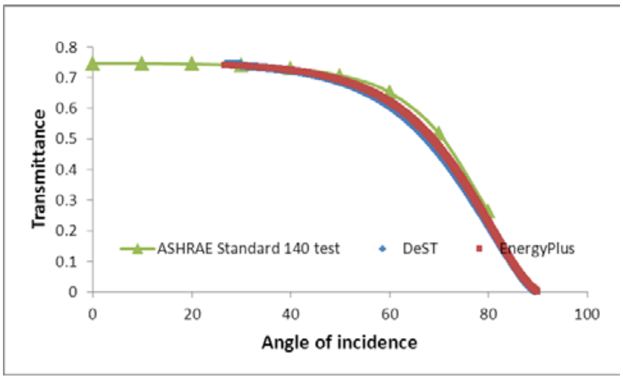

Figure 9 The Solar Transmittance at Various Incident Angles

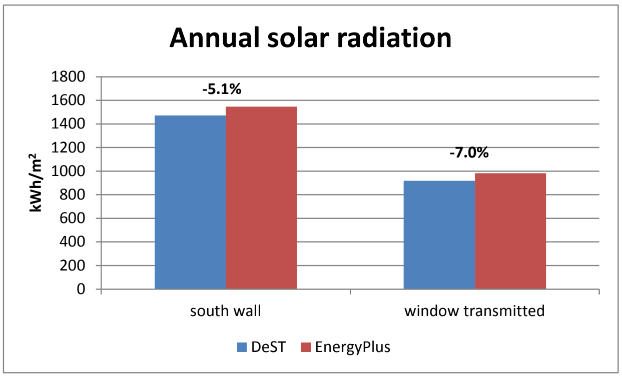

Figure 10 Annual Solar Radiation on the South Wall and the Annual Window-Transmitted Solar

The main reason for this discrepancy is the time point used for the solar position calculation and the sky diffuse solar radiation model. DeST (DeST 2006) uses the beginning of the hour for solar calculations during the hourly time-step simulations, while EnergyPlus (EnergyPlus 2010) performs interpolation of solar radiation data from weather input files, and uses the end of each sub-hourly time-step for the solar calculations. For the sky diffuse solar radiation model, EnergyPlus takes into account the anisotropic radiance distribution of the sky, while DeST uses an isotropic model.

Comparing the results between C9 and C10, we can find that another main influencing factor is the surface convection coefficients. EnergyPlus calculates the coefficients considering the variations of indoor and outdoor conditions, while DeST uses constant values as required by the linear system structure of its state space heat balance method. As both exterior and interior surface convection coefficients are smaller in EnergyPlus than in DeST, EnergyPlus produces lower annual heating loads and higher annual cooling loads.

In conclusion, the differences between annual heating or cooling loads from EnergyPlus and DeST can be controlled below 10% if inputs including default values or algorithms are matched, although EnergyPlus and DeST have difference in their load calculation algorithms and modeling assumptions. Therefore, matching inputs are the key when using different BEMPs.

4.2 Double-room cases under extreme thermal conditions

4.2.1 Specification of test cases

DOE-2.1E (DOE-2 1982) lacks strict zone and surfaces heat balance calculations. It calculates the interior surface long-wave radiation exchange by using the combined convective and radiative heat transfer coefficients, rather than calculating the convection from surfaces to zone air, and long-wave radiation between interior surfaces separately. DOE-2.1E also uses a constant space temperature to first estimate the building loads. These are further adjusted later to consider the variation from thermostat settings and outdoor air ventilation. Furthermore, DOE-2.1E uses the adjacent space temperature from the previous time step to calculate the heat transfer from adjacent spaces. This can cause some errors if two adjacent spaces are not conditioned, or if there is a large temperature difference between two adjacent spaces.

To see how this limitation affects DOE-2 calculation results, Case EC1 was designed for the three BEMPs. A building has two adjacent rectangular spaces each with dimensions 10 m wide × 10 m long × 3 m high, as shown in Figure 11. Room 1 is conditioned with a special thermostat setting while Room 2 is un-conditioned.

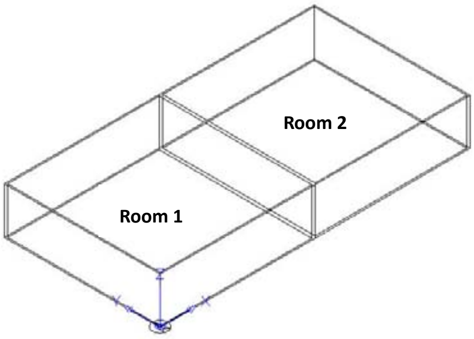

Figure 11 Geometry of the Building for Case EC1

The construction of the exterior walls, roof and floor are the same as Case 600 and the interior walls are the same as Case 960 in ASHRAE Standard 140-2007. All solar/visible absorptance and thermal emissivity coefficients are set to zero, so only convective heat transfer between the outdoor air and the two indoor zones is considered. Surface convection coefficients are specified as the same constant values for DOE-2.1E, EnergyPlus, and DeST. The outdoor air temperature and ground temperature are always kept at 10℃. Each zone has no internal gains or air infiltration.

4.2.2 Results and discussion

The air temperature of Room 1 varied periodically (switched between 29.8℃ and 16.2℃ hourly) all year round due to a scheduled air-conditioning system, as shown in Figure 12. The room temperature of Room 2 was then calculated, as shown in Figure 13, which shows that the results from DeST and EnergyPlus were always constant, but DOE-2.1E gave fluctuating room air temperatures between 13.8 and 14.4℃. This is mainly due to the fact that DOE-2.1E uses the adjacent room temperature from the previous time-step to calculate the heat transfer between adjacent zones, and the heat flow through the interior walls and partitions is treated as steady-state.

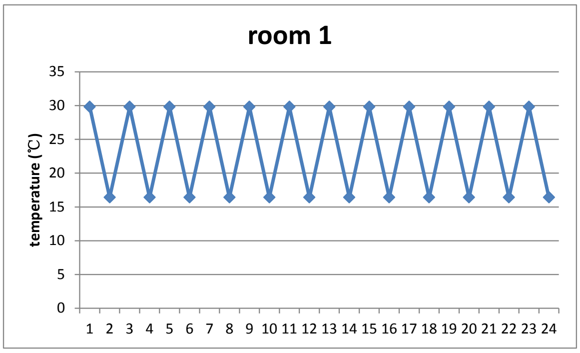

Figure 12 Temperature Settings of Room 1

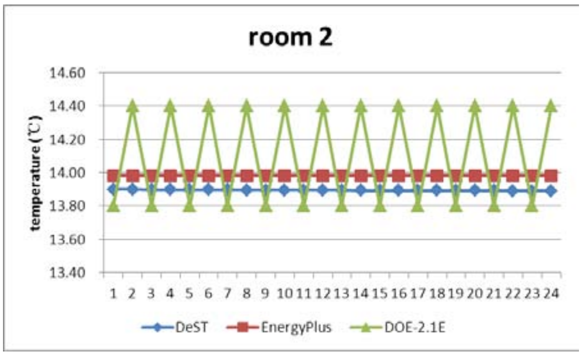

Figure 13 Simulated Temperature of Room 2

4.3 Double-room cases under practical engineering conditions

The results from Case EC1 implied that DOE-2.1E has limitations in accurately calculating heat transfer between adjacent zones. Further tests were designed to ascertain the influence of this under practical engineering conditions.

4.3.1 Specification of test cases

Three new tests were created. Case SC1 is the base test and its results are used as the baseline for Cases SC2 and SC3. The building model of all the three cases includes two zones and each zone has dimensions 10 m wide × 10 m long × 3 m high, with a window area of 12 m^2 on the south facade.

Table 10 Test Cases under Practical Engineering Conditions

Case	Description
SC1	Base test, both rooms are conditioned 24 hours a day
SC2	Room 1 with office daytime occupancy; Room 2 empty and unconditioned
SC3	Room 1 with bedroom nighttime occupancy; Room 2 empty and unconditioned

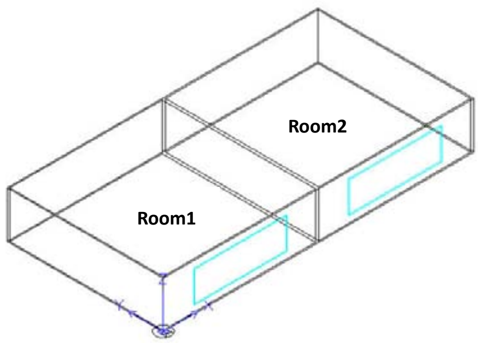

Figure 14 Building model of Case SC1

Weather data was the same as for Case 600. The constructions of the exterior walls, roof and floor, as well as the properties of the double-pane window, were the same as for Case 600. The interior wall was the same as for Case 960 in ASHRAE Standard 140-2007. Infiltration was always 0.5 air changes per hour, DeST and EnergyPlus use constant values, while DOE-2.1E uses the AIR-CHANGES/HR method which calculates the infiltration based on the wind speed. Internal heat gains from people, lighting, and equipment were assumed as constant. Table 11 lists the input assumptions for the internal heat gains.

Table 11 Internal Heat Gains for Case SC1

	DOE-2.1E	**DeST**	**EnergyPlus**
People	0.1 People/m^2 Sensible heat: 66 W Latent heat: 71 W	0.1 People/m^2 Sensible heat: 66 W Latent heat: 0.102 kg/h	0.1 People/m^2 Active level: 137 W Sensible heat fraction: 0.48
People heat distribution	Default weighting factors	Default distribution	Same as DeST
Lighting	10 W/m^2	10 W/m^2	10 W/m^2
Lighting heat distribution	Default lighting type	Default distribution	Same as DeST
Equipment	5 W/m^2	5 W/m^2	5 W/m^2
Equipment heat distribution	Default weighting factors	Default distribution	Same as DeST

Solar and visible absorptances were set to 0.6, thermal emissivity to 0.9, and ground reflectance to 0.2 in the three BEMPs. Surface convection coefficients, solar distribution, and time-step were set to the default values or algorithms in each BEMP.

DeST and EnergyPlus use ideal air systems and DOE-2.1E uses a “two pipe fan coil” system. The system used in DOE-2.1E was set to be a 100% convective air system, 100% efficient with no duct losses, and with adequate cooling and heating capacities, (which is very close to an ideal air system). The air systems were always on and the zone thermostat set-point for Case SC1 was always 21.1℃. In Cases SC2 and SC3, the set-point for heating was 20℃ and for cooling was 27℃. SC2 was exactly the same as SC1 except that Room 1 used an office daytime schedule and Room 2 was empty and unconditioned (no internal gains).

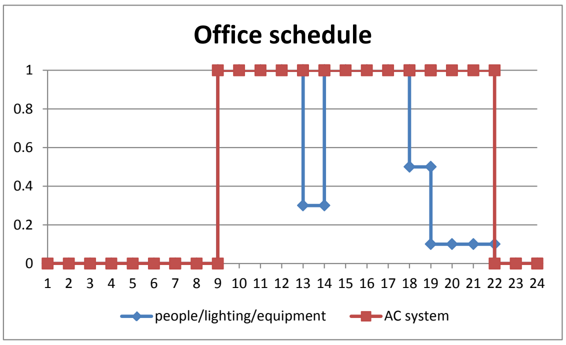

Figure 15 Office daytime schedule used in SC2

SC3 is exactly the same as SC2 except that Room 1 used a bedroom nighttime schedule.

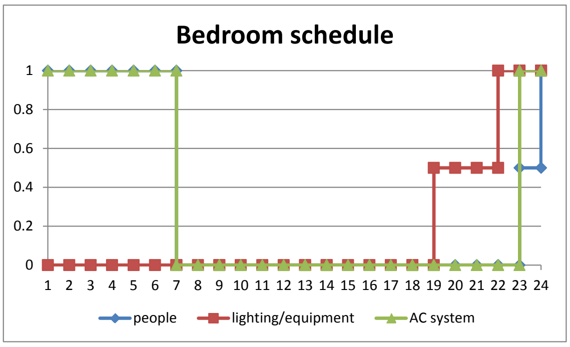

Figure 16 Bedroom nighttime schedule used in SC3

4.3.2 Results and discussion

In DOE-2.1E, hourly heating or cooling loads are calculated by the LOADS subprogram, first assuming constant space temperature, then adjusted by the SYSTEMS subprogram to consider the thermostat settings, outdoor air ventilation, etc. The loads from the SYSTEMS subprogram are used in our study.

Comparing the results of different BEMPs from SC1 to SC3, heating loads were always close but cooling loads were not. From the results of SC1, the monthly cooling loads of the three BEMPs were very close. Comparing SC1 with SC2 and SC3, we can see that the monthly cooling loads of DeST and EnergyPlus were always close, but the results of DOE-2.1E deviate more significantly. In SC1 there was no heat transfer between adjacent zones, so its results can be used as the benchmark where the biggest difference between annual cooling loads from DOE-2.1E and EnergyPlus was 10.3%. In SC2 the annual cooling load of DOE-2.1E was 35.0% higher than DeST and 18.2% higher than EnergyPlus. In SC3 the annual cooling loads were very small compared to SC1 and SC2, so the percentage differences, even though very high, are not very meaningful. These results reveal that DOE-2.1E has serious limitations in accurately accounting for multi-zone heat balance and part-time operation of HVAC systems, especially for the nighttime air-conditioning case SC3.

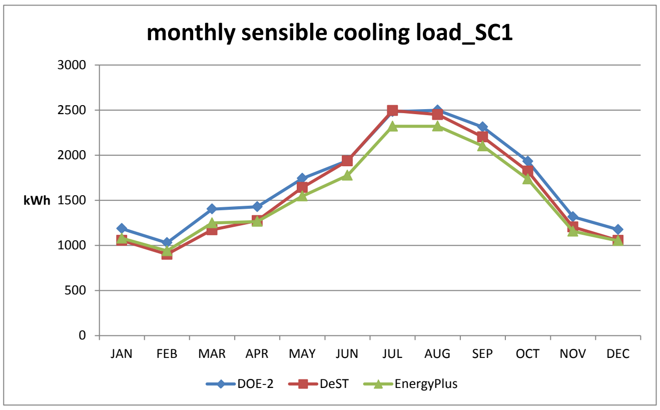

Figure 17 Monthly Cooling Loads of SC1

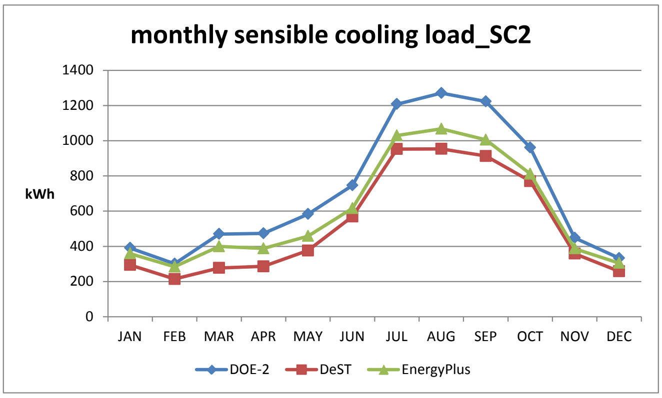

Figure 18 Monthly Cooling Loads of SC2

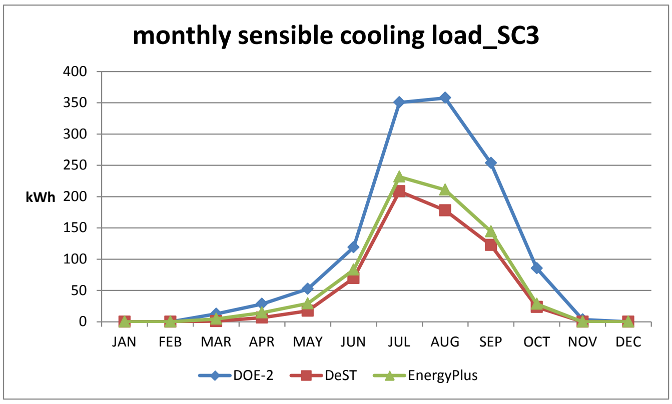

Figure 19 Monthly Cooling Loads of SC3

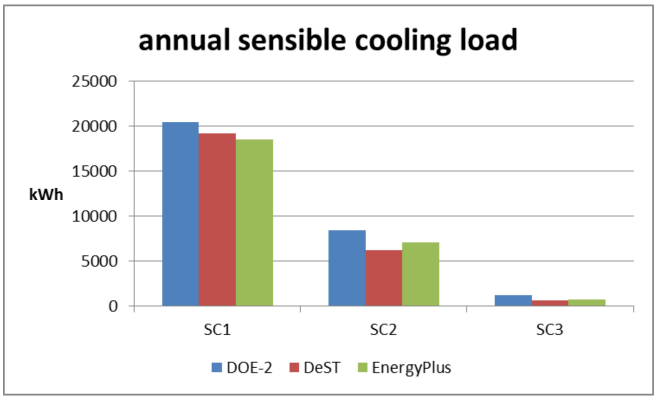

Figure 20 Annual Cooling Loads from SC1 to SC3

From the monthly heating results (Figures 21 to 23) from the three BEMPs, DeST and EnergyPlus always have close simulation results across all three test cases, but DOE-2.1E's results are always lower, mainly due to the differences in default values and algorithms used. For all three cases SC1 to SC3, the annual heating loads (Figure 24) from DOE-2.1E were about 20% lower than those from EnergyPlus or DeST.

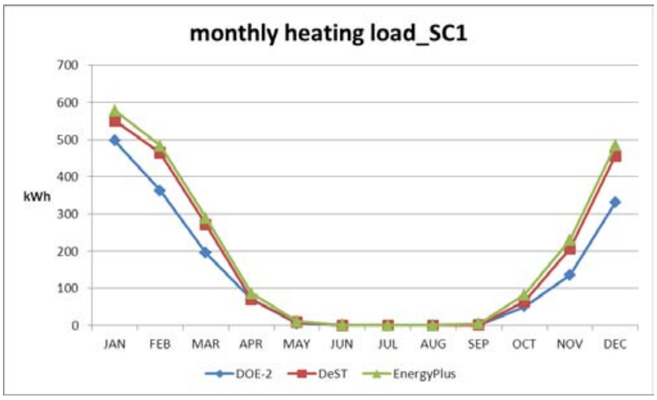

Figure 21 Monthly Heating Loads of SC1

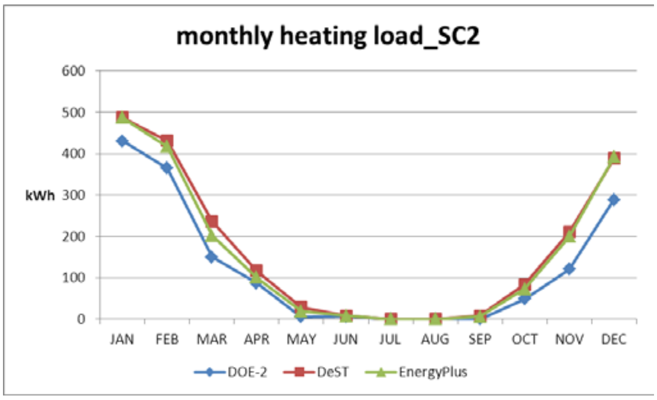

Figure 22 Monthly Heating Loads of SC2

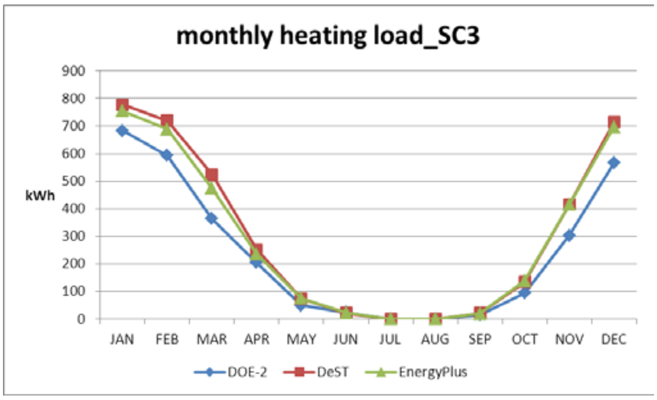

Figure 23 Monthly Heating Loads of SC3

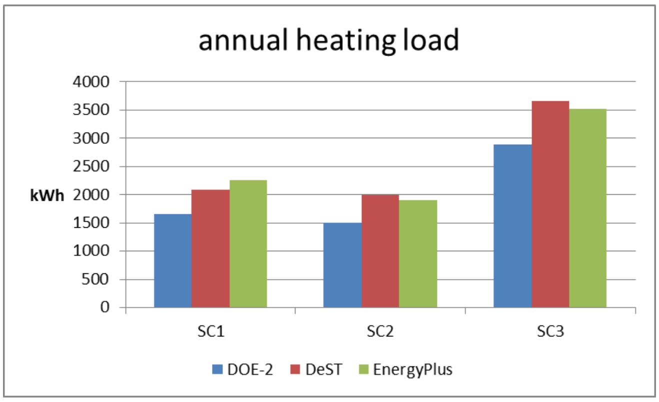

Figure 24 Annual Heating Loads from SC1 to SC3

5 Conclusions

This paper compared the capability and simulation results of EnergyPlus, DeST and DOE-2.1E for performing building thermal load calculations, to evaluate the impact of the different simulation engines. Algorithms used to calculate the thermal loads play an important role, but keeping inputs to energy models exactly the same or equivalent is even more important to guarantee consistent results from different BEMPs. All the three BEMPs have the basic capability for performing building load calculations, and the discrepancy in load results from DeST and EnergyPlus was reduced to less than 10% if the surface convection coefficients were set exactly the same as those in ASHRAE 140 test cases.

To differentiate this paper from previous work, this comparison study did not produce another test suite, but rather a methodology to design tests and a process to carry out these tests. A few in-depth tests, built upon the ASHRAE 140 tests, were designed and performed to identify and quantify the key influencing factors that drive the discrepancies in results from EnergyPlus, DeST and DOE-2.1E. It was found that DOE-2.1E has limitations in handling heat transfer between adjacent zones, with large errors emerging for cases when adjacent zones have very different conditions, or if a zone is part-time conditioned when adjacent zones are unconditioned.

This paper covers the loads comparison between EnergyPlus, DeST and DOE-2.1E. A future paper will discuss the methods and findings from comparing the HVAC models, including whole building simulations using the three programs for a real building with utility bills.

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